

SCALAR MEDIATED FCNC AT THE FIRST MUON COLLIDER

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In the most general two-Higgs doublet model (generally referred to as Model III), tree level scalar-mediated flavor changing neutral couplings exist. It has been noted that the most natural value for such a coupling is of the order of the geometric mean of the Yukawa couplings of the two fermions. Bounds on those couplings that involve the second and third generations, from τ , B , D and μ physics, are very weak and are not sensitive to this “natural” value. In this paper, it is pointed out that the process $\mu^+\mu^- \rightarrow \mu\tau$, at a muon collider tuned to the scalar resonance, will easily reach this sensitivity if the scalar mass is below 140 GeV. Hundreds of events are expected for an integrated luminosity of an inverse femtobarn, and there appears to be no background. Failure to observe this process, if the scalar is below 140 GeV, would effectively rule out Model III.

The most important unanswered question in the Standard Model(SM) is the nature of electroweak symmetry breaking. Should the Higgs bosons and/or additional scalars be discovered in the next few years at either the Tevatron or the LHC, it will be crucial to explore the properties of these particles in detail. A primary motivation for the muon collider[1] is that a large number of scalars can be produced through s-channel resonance, and thus a muon collider could be a “Higgs” factory.

The capabilities of a muon collider for exploring Higgs physics in the Standard Model and in the Minimal Supersymmetric Standard Model(MSSM) have been explored extensively[1]. The simplest extension of the Standard Model is the two-Higgs doublet model(2HDM). In this model, tree level flavor changing neutral currents (FCNC) will naturally occur. This is because there are two Yukawa coupling matrices, and thus diagonalization of the quark mass matrix will not automatically diagonalize each of the Yukawa matrices. These FCNC are phenomenologically dangerous, leading, for example, to large contributions to $K^0 - \overline{K}^0$ mixing.

It is important to note that one can always choose a basis in which one scalar field acquires a vacuum expectation value and the other does not. In this case, the latter does not participate at all in electroweak symmetry breaking and is the only scalar with FCNC couplings, and there is no *a priori* reason that its mass should be light. If its mass is greater than a few TeV[2], there is no FCNC problem. This is the most straightforward solution, and the effective theory below a TeV is then just the standard model.

However, when people refer to the 2HDM, they generally refer to the situation in which this extra scalar is light, with a mass on the order of

the electroweak scale.¹ In this case, something must suppress the flavor-changing couplings.

One method of suppression[3], which eliminates tree-level FCNC completely, is to assume that a discrete symmetry either couples all of the fermions to only one of the scalar doublets (Model I) or else couples one doublet to the $Q=2/3$ quarks and the other to the $Q=-1/3$ quarks (Model II). Such a discrete symmetry is completely *ad hoc*. Note that Model II type couplings automatically occur in the MSSM, but if an additional pair of Higgs doublets is added to the MSSM, the same problem recurs.

Another method of suppression is to assume that the flavor-changing neutral couplings are small. It was pointed out in Ref. [4] that in a variety of mass matrix models, the FCNC couplings are approximately given by the geometric mean of the Yukawa couplings of the two fermions (this is now referred to as Model III). With this ansatz, the FCNC couplings involving the first generation fields are very small, and the bounds are not as severe. The largest flavor-changing couplings will then involve those between the second and third generations. The FCNC couplings can only be bounded phenomenologically, and there are several detailed analyses of these bounds[5, 6], coming from K , D , B and τ physics.

What will a muon collider be able to tell us about Model III? Atwood, Reina and Soni[7] showed that the process $\mu^+\mu^- \rightarrow H \rightarrow t\bar{c} + \bar{t}c$ could occur at an easily observable rate, since the geometric mean of the top and charm Yukawa couplings is greater than the bottom quark Yukawa coupling. Depending on parameters, one could detect large numbers of

¹This would involve fine-tuning, of course, but no more fine-tuning than in the MSSM, where the SUSY breaking scale and the electroweak scale are logically independent.

events, with an integrated luminosity of an inverse femtobarn, if the scalar mass exceed 180 GeV.

In this Letter, another signature of Model III, which is both cleaner than the hadronic signature and which does not require the scalar to be heavier than the top quark, is discussed. This signature is $\mu^+\mu^- \rightarrow H \rightarrow \mu\tau$. For a 120 GeV scalar, for example, one would see a 60 GeV muon back-to-back with a 60 GeV tau. Since any other process that produces a high-energy muon will result in a muon with less than half the center-of-mass energy, there will be no background. We will see that there will be large number of events, and failure to detect this signal would virtually rule out Model III.

Let us first consider the Yukawa interaction of two scalar doublets to fermions

$$\mathcal{L} = \eta_{ij}^U \overline{Q}_i \tilde{\phi}_1 U_j + \eta_{ij}^D \overline{Q}_i \phi_1 D_j + \eta_{ij}^L \overline{L}_i \phi_1 E_j + \xi_{ij}^U \overline{Q}_i \tilde{\phi}_2 U_j + \xi_{ij}^D \overline{Q}_i \phi_2 D_j + \xi_{ij}^L \overline{L}_i \phi_2 E_j \quad (1)$$

In this Letter, we will consider the neutral fields only, and will ignore possible CP violation, focusing on the CP-even scalars.

Without loss of generality, one chooses a basis such that only one scalar, ϕ_1 , acquires a VEV, $v = 246$ GeV, and the other, ϕ_2 , does not (thus, ϕ_2 does not participate in symmetry breaking and does not really deserve the label “Higgs boson”). The Yukawa interactions of ϕ_1 are proportional to the mass matrix and are therefore flavor-diagonal, whereas the Yukawa interactions of ϕ_2 are arbitrary and give FCNC. In order to prevent tree level FCNC, one must impose a discrete symmetry in Eq. 1, such as $\phi_2 \leftrightarrow -\phi_2$. In Model III, no such symmetry is imposed.

For experimental purposes, one should use the physical mass basis for

the Higgs bosons, h and H . We define the h field to be the lighter of the two. In the conventional notation, this basis is rotated by an angle α from the basis of Eq. 1. Ignoring the imaginary part of the Yukawa couplings, the couplings of the h field to $\bar{f}_i f_j$ is

$$C_{h f_i f_j} = -\frac{g}{2} \frac{m_i}{M_W} \delta_{ij} \sin \alpha + \frac{\xi_{ij}}{\sqrt{2}} \cos \alpha \quad (2)$$

It was suggested by Cheng and Sher[4] that the most natural value for the ξ_{ij} , which occurs in many mass-matrix models, is given by the geometric mean of the Yukawa couplings of the two fermions, i.e. writing

$$\frac{\xi_{ij}}{\sqrt{2}} = \lambda_{ij} \frac{g}{2} \frac{\sqrt{m_i m_j}}{m_W} \quad (3)$$

one expects to have $\lambda_{ij} \simeq 1$.

There have been a number of papers[4-15] examining Model III and constraining the allowed values of λ_{ij} (where $i \neq j$). The most extensive analyses are those of Refs. [5],[6]. In the former, limits from rare τ and rare B decays were considered, and in the latter, effects from $F^o - \bar{F}^o$ (where $F = K, D, B, B_s$), $e^+ e^-(\mu^+ \mu^-) \rightarrow t\bar{c} + c\bar{t}$, $Z \rightarrow b\bar{b}$, $t \rightarrow c\gamma$ and the ρ parameter were considered. The result of these analyses show that $\lambda_{ds}^D \ll 1$, $\lambda_{db}^D < 1$ and $\lambda_{uc}^U < 1$. In other words, the FC couplings involving the first generation seem to be very small.

There are several 2HDM models[17, 18] in which the λ_{ij} involving the first generation are much smaller than one, and one might argue that the extremely small Yukawa couplings of the first generation might be subject to perturbations from physics at a very high scale. A true test of Model III would be to examine FC couplings involving the second and third generations (if *those* are small, then Model III would be excluded). This might

be particularly interesting in view of the fact that the atmospheric neutrino problem indicates[19] very large mixing between the second and third generations in the neutrino sector. However, looking at rare τ and rare B decays[5] can not reach the $\lambda_{\mu\tau} \simeq 1$ or $\lambda_{bs} \simeq 1$ sensitivity without an improvement of many orders of magnitude over current limits, and $B_s - \overline{B}_s$ mixing is already maximal. One can consider $t \rightarrow c\gamma$, but the branching fractions are very small. The decay $t \rightarrow ch$ is promising[12], although the branching fraction is less than a percent (for $\lambda_{ct} = 1$). Recently, a very extensive analysis of detection of $t \rightarrow ch$ at the LHC has been carried out[16]. There it was shown that one would be able to detect the decay for $\lambda_{ct} = 1$ fairly easily, and that failure to detect the signal would give $\lambda_{ct} < 0.12$. There has also been a detailed analysis[20] of top-charm production at the NLC; although the signature is fairly clear due to the distinct kinematics, the rate remains small.

At a muon collider, one will be produce scalar bosons as an s-channel resonance, and tens of thousands of scalars will be produced directly. Atwood, Reina and Soni[7] showed how the process $h \rightarrow t\bar{c} + \bar{t}c$ would have a very distinctive signature and a high event rate. However, it does require the scalar to have a mass above 180 GeV.

Since large mixing has only been observed in the neutral lepton sector between the second and third generations, one naturally would want to look at the charged lepton sector, i.e. at $\lambda_{\mu\tau}$. The muon collider provides a “smoking gun” signature for this coupling—the decay $h \rightarrow \mu\tau$. This will have a high event rate, and zero background.²

²This decay was considered in the context of the Tevatron (where the scalar is produced off-resonance) in Ref. [15]. They showed that if the current bound on $\lambda_{\mu\tau}$ is saturated, a signal of $h \rightarrow \mu\tau$ could be seen at the Tevatron.

The cross section for production of a state X at the muon collider, convoluted with the collider energy distribution, is given by[1]

$$\sigma_h \sim \frac{4\pi}{m_h^2} \frac{B(h \rightarrow \mu^+ \mu^-) B(h \rightarrow X)}{\left[1 + \frac{8}{\pi} \left(\frac{\sigma_{\sqrt{s}}}{\Gamma_h}\right)^2\right]^{1/2}} \quad (4)$$

where the B are the branching ratios, Γ_h is the total width and the Gaussian spread in the beam energy \sqrt{s} is given by $\sigma_{\sqrt{s}} = \frac{R}{\sqrt{2}} \sqrt{s}$, with R the energy resolution of each beam. The energy resolution is expected to be in the range 0.005%–0.05%. We will look at relatively light scalars; for $m_h < 140$ GeV, the Higgs boson is narrow and the cross section is proportional to Γ_h/R .

The result depends on the couplings of the scalar to μ pairs as well as $\mu - \tau$. For the former, we will not include a possible $\xi_{\mu\mu}$ contribution—this is unknown and is expected to be of the same order as the standard model contribution. Note that any enhancement in this coupling will be determined as soon as the resonance is found at the muon collider. For the $\mu - \tau$ coupling, we will assume that $\lambda_{\mu\tau} \cos \alpha = 1$ (the cross section will, of course, scale as $\lambda_{\mu\tau}^2 \cos^2 \alpha$). Since the total width of the scalar boson is (for masses below about 140 GeV) dominated by b -quark decays, we have

$$\Gamma_h = \frac{3g^2 m_b^2 m_H}{32\pi m_W^2} \quad (5)$$

$$B(h \rightarrow \mu^+ \mu^-) = \frac{1}{3} \frac{m_\mu^2}{m_b^2}, \quad (6)$$

and

$$B(h \rightarrow \mu^+ \tau^-) = \frac{1}{3} \frac{m_\mu m_\tau}{m_b^2} \quad (7)$$

For an integrated luminosity of 1 femtobarn, and a resolution of $R = 0.005\%$ (both of which are achievable), the total number of events is given

by (930, 740, 540, 330, 100, 1) for $m_h = (100, 110, 120, 130, 140, 150)$ GeV. Note that for larger masses, the rate drops considerably since new decay channels open up and the branching ratios drop substantially. The event rate also scales as $1/R$, should the given resolution not be achievable.

We see that for masses below 140 GeV, we expect hundreds of events in an inverse femtobarn. The signal would be dramatic. One would see a muon and a tau each with an energy of half the center-of-mass energy. The impact parameter for tau decays at this energy is approximately 100 microns[21], which should be resolvable. But even if the tau vertex can not be seen, the mere presence of a muon with half the beam energy (and no muon of similar energy on the other side) would indicate new physics, and the decays of the tau will provide a smoking gun for this model. There appears to be no substantial background; any other particles produced which decay into muons will have the muon energy degraded.

Suppose the scalar has a mass of 120 GeV. Then failure to see any signal would put an upper bound on $\lambda_{\mu\tau} \cos \alpha$ of substantially less than 0.1 (and $\cos \alpha$ would likely be determined when the scalar is initially discovered). Since this is expected to be the largest coupling, such a bound (coupled with failure to observe $t \rightarrow ch$ at the LHC[16]) would effectively rule out Model III.

What about other flavor-changing processes? One can look for $\mu^+\mu^- \rightarrow e\tau$ just as easily. However, here the number of events expected (for $\lambda_{e\tau} \cos \alpha = 1$) is down by a factor of $m_\mu/m_e \sim 200$. Thus, one would expect only a few events. Nonetheless, the background is negligible, and this would provide the best bound on $\lambda_{e\tau}$ (and would provide a good check if the $\mu\tau$ signature is seen). One can also look for $\mu^+\mu^- \rightarrow \bar{b}s + b\bar{s}$, which would constitute

roughly 3% of all decays, but the background from $b\bar{b}$ would probably rule out substantive limits.

If the scalar mass is below 140 GeV, then Model III predicts hundreds of $\mu\tau$ events will be observed at the first muon collider. Although one can never experimentally rule out tree level flavor changing neutral couplings at some level, the primary motivation for Model III requires that the largest flavor changing couplings give $\lambda \sim 1$. The muon collider will thus provide a definitive test of this Model.

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